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Sand dune restoration experiments at Bei-Men Coast, Taiwan

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ABSTRACT

The Bei-men barrier beach in southwestern Taiwan is a coastal plain with rivers, tidal channels and lagoons. Together with dunes and associated water bodies, the beach and tidal flats provide valuable habitat for many fauna and flora. However, in the last 3 decades, due to both natural and anthropogenic activities, the barrier beach and sand dunes eroded rapidly. As a result, not only is the habitat progressively destroyed, but also the lives and properties of nearby residents are threatened. It is well known that, sand dunes on barrier beaches can serve as a natural buffer against high waves in stormy weathers, preventing or delaying the intrusion of water and sediment into lagoon areas. As compared with other hard engineering measures, dune nourishments and/or reconstructions are more preferred in a more demanding society. These are considered as the so-called ecological solutions. To guarantee a sustainable development for the Bei-men barrier beach, experiments on sand dune restoration and nourishment were carried out. The main objective of these experiments is to find the best possible way to build sand dunes that should be both economically, as well as ecologically, feasible. To achieve this, all the materials applied are required to be either locally available, and/or biodegradable. It is shown that, the bamboo fences are the most efficient setup to nourish sand dunes. The newly nourished dunes are then covered with dried giant *Miscanthus* (*Miscanthus floridulus*) which serves as mulches, with Littoral Spinegrass (*Spinifex littoreus*) planted atop for further stabilization. It is shown that the proposed methods are rather satisfactory, and can be valuable aids for the restoration of barrier beaches in Taiwan.

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1. Introduction

Taiwan has a total of 82 wetlands, and 34 of them, covering an area of 49 thousand hectares, are distributed in the coastal region. These coastal wetlands consist of barrier islands, lagoons, low-lying plains, or estuaries. On one hand, they act as buffers against high-energy typhoon waves, preventing or delaying intrusion of water to the inland area (Nicholls et al., 2007). On the other hand, they are natural habitats rich in biodiversity.

However, in the past few decades, all these regions are found to be in different degrees of deterioration. Studies have shown that the coastal construction works carried out in these years are the main reason for this (Hsu et al., 2006, 2007). Harbor entrance jetties, and/or estuarine training walls, in adjacent areas, for example, could intercept littoral drift. Furthermore, progressive advancing of the bulkheads seawards have reduced the littoral zone. In the meantime, sediment supplies from the rivers decreased with the constructions of reservoirs and bank revetments. As a result, there is a deficiency in sedimentary budget in the coastal area.

Wetlands are important both in ecology, as well as in coastal defense. Recognizing this, the Construction and Planning Agency of the Ministry of the Interior, hereafter referred to as CPAMI, reacted accordingly. A draft of "The Wetland Restoration and Enhancement Bill" was completed by Construction and Planning Agency, Ministry of the Interior (CPAMI) (2010).

The draft underlines both the legal and the technological aspects of the restoration of the wetlands, in which, their ecological and physical functions are stressed. According to the draft, ecosystem-based restoration approaches for the protection of barrier beaches, sand dunes, and lagoons are to be encouraged. For the case where engineering measures are necessary, their impacts on the existing wetland environments are to be minimized. Constructions of the hard engineering structures are, therefore, in principle, not to be carried out.

Sand dunes on a barrier beach which are parallel to the shore play vital roles in coastal stability, for they act as barriers against waves and tides. It is also a reservoir of sands that functions to nourish eroding beaches, and to feed the nearshore sand bars

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during storms, keeping thereby the barrier beach in a dynamic equilibrium (O'Connell, 2008). This is the reason why sand dunes are treated as one of the framework for safeguarding against coastal flooding in the "integrated coastal zone management (ICZM)" plans of many countries (Mohan et al., 2003; van Wesenbeeck et al., 2014). Thus, dunes form important links in the coastal sediment budget and need to be considered in the scope of coastal management and engineering measures (Arens and Wiersma, 1994; Saye et al., 2005). In Taiwan, where 3 to 4 typhoons may invade annually, sand dunes can be seriously eroded by high-energy waves. It would take years for these sand dunes to rebuild through natural processes. Since hard engineering methods are to be avoided, the only option left is then dune enhancement and reconstruction. Not only it is feasible and efficient, but also it is the least expensive measure against shoreline erosion (Gregorio et al., 2002).

Over the years, a variety of measures have been used effectively to build up, and to stabilize dunes, or to prevent the erosion of dunes and beaches. Devices that have been effectively implemented to trap the aeolian sand are fences, nylon nets, and rugged materials (Cong, 1991; Neves et al., 2004; Hotta and Harika, 2010). In the 'Guidelines of Barrier Beach Management in Massachusetts', snow fences and Christmas trees were used to build sand dunes and to minimize erosion (Massachusetts Barrier Beach Task Force, 1994). Sand fences in various configurations and their respective efficiencies in dune formation have also been studied and discussed in detail (see for example, Savage and Woodhouse, 1968; Waterways Experiment Station, 1984; Gravens et al., 2001 Miller et al., 2002; Williams, 2007). Sand-trapping fences have been used in Europe for some 700 years (Nordstrom, 2008). However, the design and employment of sand fences are still an approach based on trial-and-error. This is because the sand accumulation efficiency of a sand fence depends on a number of factors; most of them are locality related. Besides the characteristics of the sand fence itself, local meteorological and topographical features of the site can also be important as well. It is also noted that, once the fences were damaged, the fragments of them, or the wires used for joining the slabs could pose a potential threat to the coastal wildlife such a migrating birds, fish, and marine mammals.

Sand dunes formed through fencing are unstable and can become deteriorated rapidly. The most common practice is to stabilize them by vegetation (Khalil, 2008). However, the dunes close to the coastline are in a very harsh environment for the plants. Limited amounts of fresh water, constant salt spray, sand blasting or burial caused by the wind, and additional disturbance due to human activities, all these can be hostile to the vegetation. Experiences have shown that, the selection of plant species and adequate maintenance such as irrigation or fertilization are the key factors of successful transplant vegetation (Nordstrom, 2008; NSW Department of Land and Water Conservation, 2001). Coarse netting and mats are useful auxiliaries in protecting dunes while the transplanted dune grasses are sowed (Dahl and Fall, 1975; Qu et al., 2013). In this way, not only can the dunes be stabilized by vegetation, they can also be attractive habitats for some shore-dwelling animals.

In this paper, we describe our attempts to build up and stabilize sand dunes to turn the barrier beach of Bei-men more resistant against erosion. We will give some details of the ecological engineering setups, together with the results of their efficiencies. It is hoped that in this way, impact of the hard engineering can be avoided, in accordance with the spirit of sustainable use and management of wetland areas.

1.1. Description of the site

Bei-men barrier beach is situated at the coast of Tainan City, a city in the southwestern of Taiwan. In early years, sediments carried by the Zeng-Wen River system were deposited at the river mouth. Gradually, barrier islands and lagoons along the coast were formed. Located on the route for water birds migration in Asia, tens of thousands of migratory birds fly southwards passing this area; some even stay there for the winter. According to the web page of the Taijiang National Park (2013), almost 200 species of birds have been sighted in this area. Among them, 21, including the endangered black-faced spoonbill (*Platalea minor*), are on the IUCN Red List. Not only the land, but also the marine ecological resources, as well as the variety of the landscape resulted in the unique dynamic barrier beach ecosystem. Due to its richness in biodiversity, this area has been declared as Coastal Nature Reserve by the CPAMI. However, similar as many places of the world, the barrier system suffers from erosion due to the natural, as well as the anthropogenic effects. In Fig. 1, we show the coastline composed of digitized results of satellite images, aerial photographs, and bathymetric surveys. The trend of recession of the barrier island over the last three decades can be clearly seen. Factors leading to the evolution of the Bei-men coastline have been proposed by many researchers (see for example, CECI Engineering Consultants Inc. (2006); National Cheng Kung University Research and Development Foundation (NCKU RDF) (2011); National Cheng Kung University Hydraulic and Ocean Engineering Research and Development Foundation (NCKU HOERDF) (2012); Sinotech Engineering Services (2013)). The main causes for the erosion of the barrier beach are now summarized as follows.

High waves from typhoon are by far the most devastating factor for the recession. Normally, the sea state here is slight in summer seasons with significant wave height and period in the range of 0.93 m and 4.84 s, respectively. The tidal range is 1.13 m. This changes, however, when typhoon approaches. Waves up to 10 m have been measured occasionally. Large waves combined with storm surges, move the sand from the seaward side of the barrier island to the backside. Afterwards, the seaside is eroded, while the backside is accreted. In a sense, the barrier island rolls over toward the mainland. When this happens, even the most intensive coastal protection will not be able to keep these islands in place.

In addition, human-related activities also tend to speed up the trend of erosion in this region. The exploitation of the salt evaporation ponds by the Taiyen Company in earlier years is believed to be the main cause of diminishing littoral sediments. Constructions of harbor entrance jetties and estuarine training walls in the 70's and 80's have also changed the balance of the littoral drift in this region. This so-called "groin effect", i.e., the structures perpendicular to the coastline tend to cut off the longshore sediment transport, was not considered during the planning stage of the constructions (Anfuso et al., 2013). In this region, the dominant direction of the littoral transport is from NNE to SSW, and is governed by the monsoon wind waves in the winter season. It can be seen in Fig. 1 that sand was accumulating at the northern sides of the structures, whereas on the southern sides erosion has occurred.

An estimate has shown that, since the construction of the Zeng-Wen Reservoir in 1973, some 256 million m^3 of sediments have been retained in the reservoir basin. Among these, at least a part of them should be the source of the estuarine sediment. In other words, the sediment source for the barrier island has been largely reduced. Fig. 1 shows that, approximately 33% of the barrier island was lost in the last 3 decades.

Alarmed by the severity of the situation of the Bei-men barrier island, the authority has decided to take action. Since sand dunes are accepted as coastline protection on a landscape scale worldwide (Borsje et al., 2011), and hard engineering measures are out of the question, it is decided to nourish the sand dunes in environmental-friendly ways. The problem now becomes deciding the optimal indigenous materials and species that can be used for

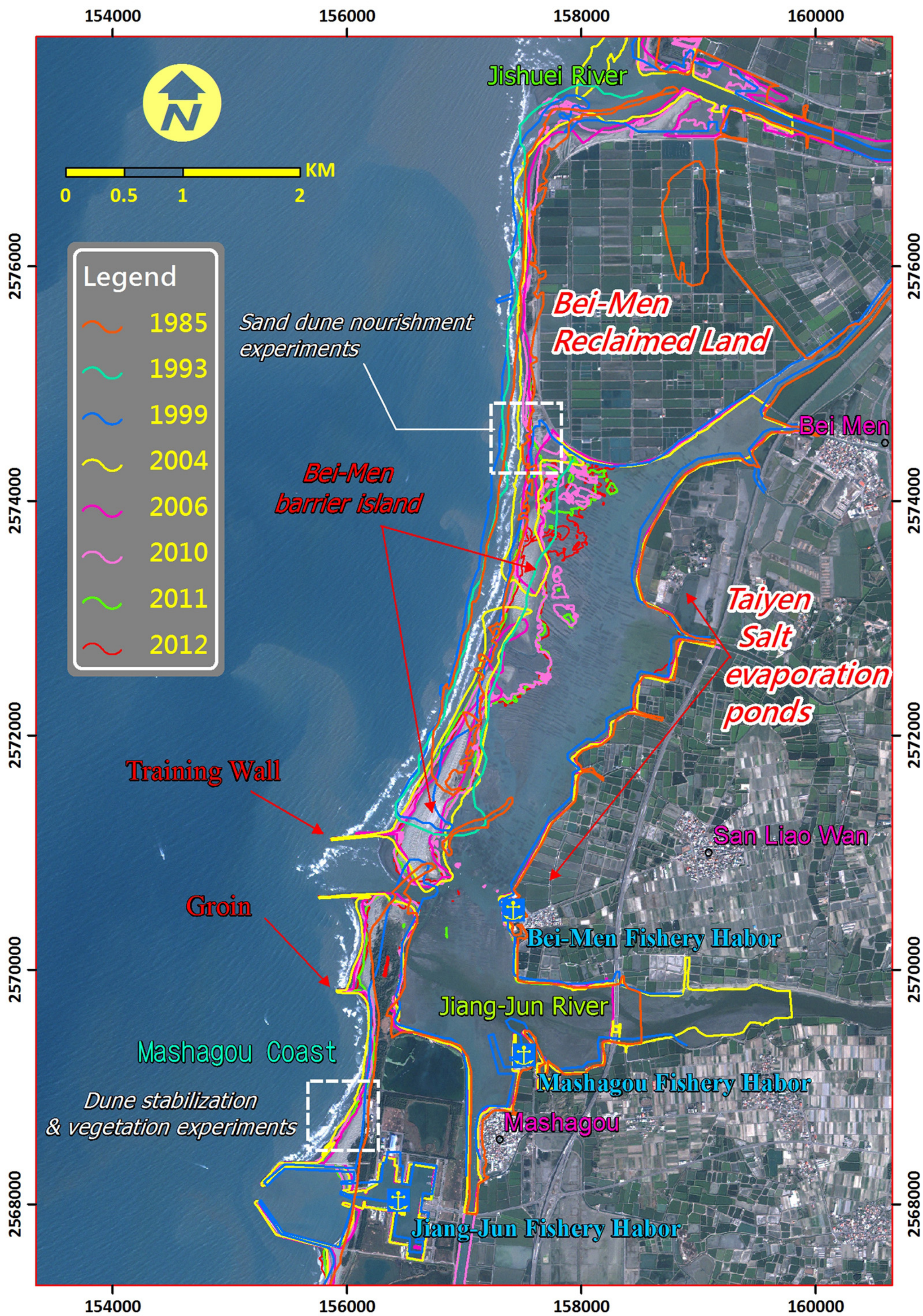

Fig. 1. Evolution of the coastlines of Bei-men Coast from 1985–2012.

sand fences and plant vegetation. In the following, we will give some detailed descriptions of the procedures taken, as well as the obtained results.

1.2. Geo-meteorological conditions

Generally speaking, there are two monsoon systems in East Asia, i.e., the East Asian winter monsoon (EAWM) in winter, and East Asian summer monsoon (EASM) in summer. The most prominent surface feature of the EAWM is the strong northeasterlies along the east flank of the Siberian high pressure system (SH, also called Mongolian High) and the coasts of East Asia (Chen et al., 2000; Wu and Wang, 2002). On the other hand, the EASM is a subtropical monsoon in which the low-level winds reverse primarily from winter northerlies to southerlies in the summer season (Ding and Chan, 2005). In Taiwan, the dominant direction of wind comes from southwest in the summer season.

To increase the chance of a successful sand fencing, it is of vital importance to have some knowledge of the characteristics of the wind on site. A year before the actual field observations were

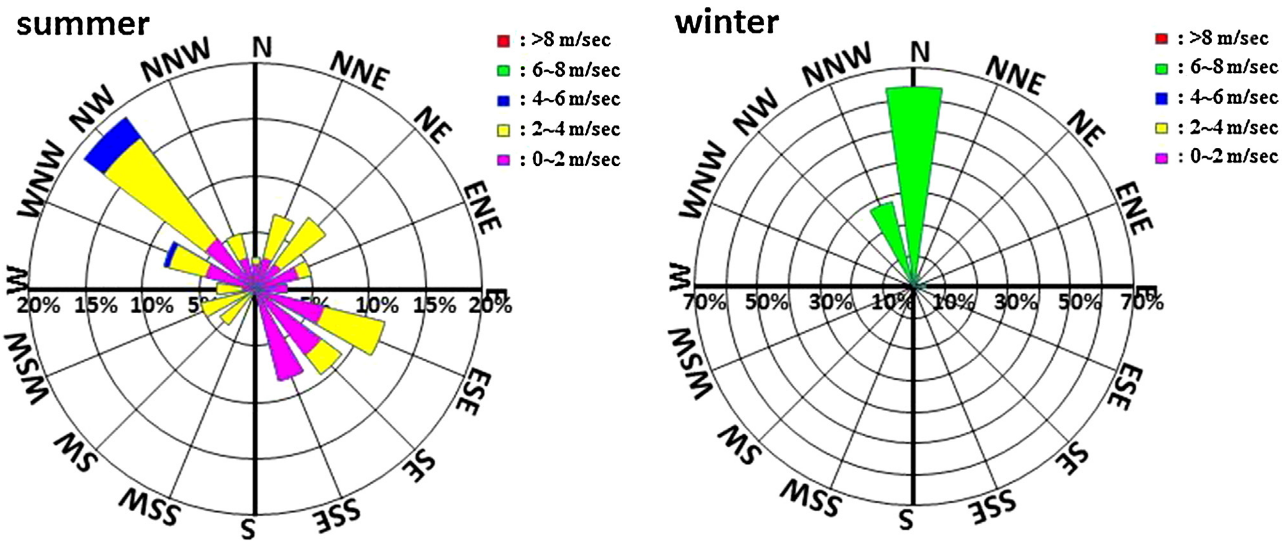

Fig. 2. Wind rose diagrams at Bei-men site (measured in July and November 2011).

carried out, the wind speed, direction and the aeolian sediment transport rates were measured in summer and winter days. Measurements were carried out for 20 days both in July and November 2011. The results are shown as wind roses in Fig. 2. From Fig. 2, it is seen that average wind speeds at a height of 75 cm above the ground are 2.12 m/s in July and 7.26 m/s in November, respectively. It is also clear that the dominant wind direction in winter is from the north.

At the same time, aeolian sediment transport rates were also measured by a sand trapper erected at the measuring site. Five heights, 12, 24, 49, 75, and 110 cm, were selected to determine the rates. The results are tabulated in Table 1. As can be seen in Table 1, the majority of the accumulated aeolian sand is less than 1 m. We estimated that the net transport rates in summer and winter are 0.09 and 0.42 g/cm-s, with prevailing directions of 146.0° and 171.7°, respectively. The distributions of the grain size of the aeolian transport at each height are summarized in Table 2. The ratio of sand to silt decreased rapidly at the height of 49 cm above the ground.

It is clear that the aeolian sand transport rate in winter is roughly 4.7 times more than that in summer. In addition, as mentioned earlier, summer is the typhoon-rich season in Taiwan. Taking these into consideration, it was therefore decided that: (1) experiments on dune restoration are to be conducted in the following winter, (2) sand fences should not exceed 1 m in height, and (3) the general direction of the fences is ENE-WSW, to ensure a greater chance of success of the experiment. In the Section 2, we will give some details of our experiments.

2. The experiments

The benefits of sand dunes to a coastal region are fourfold (Virginia Marine Resource Commission, 1993). They are, flood and erosion protection, sand replenishment, providing habitat for coastal fauna, and increasing the scenic value of the coast (Anfuso et al., 2014). To minimize further erosion caused to the barrier beach by waves and surges, the authorities decided to build stable foredunes in long strips. It has also been decided to do this in the most economic and ecological possible way. Thus, our experiments consist of three parts: sand dunes building, their stabilization, and vegetation transplanting. The experimental sites are marked in Fig. 1.

Different setups with various materials were used to assess their efficiencies in sand dune restoration. All the experiments were conducted in the winter monsoon season. It should be mentioned that, to shorten the time needed, we have somewhat modified the sequence of our experiment. In the usual way, dune stabilization follows sand dune building. However, as the time limit of the contract was 1 year, we decided to carry out all the three experiments at the same time and used bull-dozed dunes for the stabilization experiments.

2.1. Sand dune nourishments

The primary objective of this experiment was to determine the most suitable materials to be used for sand fencing. It is believed that, being both natural and locally available, the impacts on the environment should be kept minimal. The experiments were carried out on the northern Bei-men beach, which is relatively flat with a 1/100 slope and is 150–200 m in width. 3 layouts were used to assess their capability in building up sand dunes. These are (1) bundles of dried giant *Miscanthus* bound to bamboo piles, (2) pile-ups of marine debris such as driftwoods and bamboo racks, and (3) sand fences constructed with bamboos. In addition, an empty field with no additional 'add-ups' was marked for

Table 1
Measured aeolian sediment transport in heights and directions.

Height above ground (cm)	Direction (g) summer/winter							
	N	NE	E	SE	S	SW	W	NW
12	34.8/84.4	8.4/69.9	5.6/7.4	7.0/16.7	11.9/8.3	6.2/9.6	7.2/5.8	53.1/52.3
24	11.9/39.5	3.1/9.3	2.0/2.3	2.0/3.2	1.9/3.7	2.0/4.5	2.9/4.6	12.9/32.3
49	0.2/18.3	0.2/3.9	0.0/1.9	0.2/2.2	0.0/3.4	0.6/3.7	0.3/5.6	0.3/9.7
75	0.0/6.0	0.0/1.0	0.0/0.6	0.0/0.3	0.0/1.2	0.0/2.7	0.0/1.5	0.0/5.9
110	0.0/0.9	0.0/0.3	0.0/0.2	0.0/0.1	0.0/0.3	0.0/0.7	0.0/0.3	0.0/0.9

The net transport rate (g/cm-s): 0.09/0.42. The main direction: 146.0°/171.7°.

Table 2
Grain-size distributions and ratios of the aeolian sediments at different heights.

	D_{10} (μm)	D_{50} (μm)	D_m (μm)	C_u	Gravel (%)	Sand (%)	Silt (%)
Height above ground (cm)	112.00	189.30	181.69	1.84	0.00	96.74	3.26
12	100.78	153.86	147.31	1.63	0.00	96.10	3.90
24	87.99	148.08	142.40	1.81	0.00	93.46	6.54
49	37.41	147.40	138.14	4.31	0.00	82.80	17.20
75	7.93	30.21	40.38	4.64	0.00	14.02	85.98
110	2.72	21.04	34.43	9.96	0.00	11.51	88.49

comparison. All test fields were of 12 m × 24 m, with the longer sides facing the dominant wind direction of NNW-SSE. It is stressed that, all the materials used in this experiment were natural and/or biodegradable so that there would be no environmental or health concerns.

(1) Bundles of dried giant *Miscanthus* on bamboo pole

Giant *Miscanthus* is treated as weeds, and can be seen in small groups on water edges all around Taiwan. In the experiment, dried giant *Miscanthus* was tied with hemp rope to a bamboo post at heights of 30, 60, and 90 cm above the ground. Three spacing, 2, 3, and 4 m, of the bamboo posts were used for comparison. Once a dune is formed, the bamboo posts will be pulled out, and the giant *Miscanthus* is left to decompose and serve as an organic fertilizer for the transplant vegetation. A sketch and the arrangement of this setup can be seen in Fig. 3(a).

- Mounds of marine debris

At times, marine debris such as driftwoods or broken bamboo racks used for oyster breeding can accumulate on the coastlines of Taiwan after floods linked to typhoons. The contaminated zone can be too large that areas are cleaned according to their priority. It seems to be a win–win solution if they can be reused for sand dune building. The debris was therefore gathered and stacked to have a dimension of, roughly, 12 × 24 × 1 ($W \times L \times H$, in meters). It is hoped that, with the rugged surface and the abrupt change of the topography, aeolian sands will be trapped more easily. With time, sands will fill up the gaps of the debris and, eventually bury them

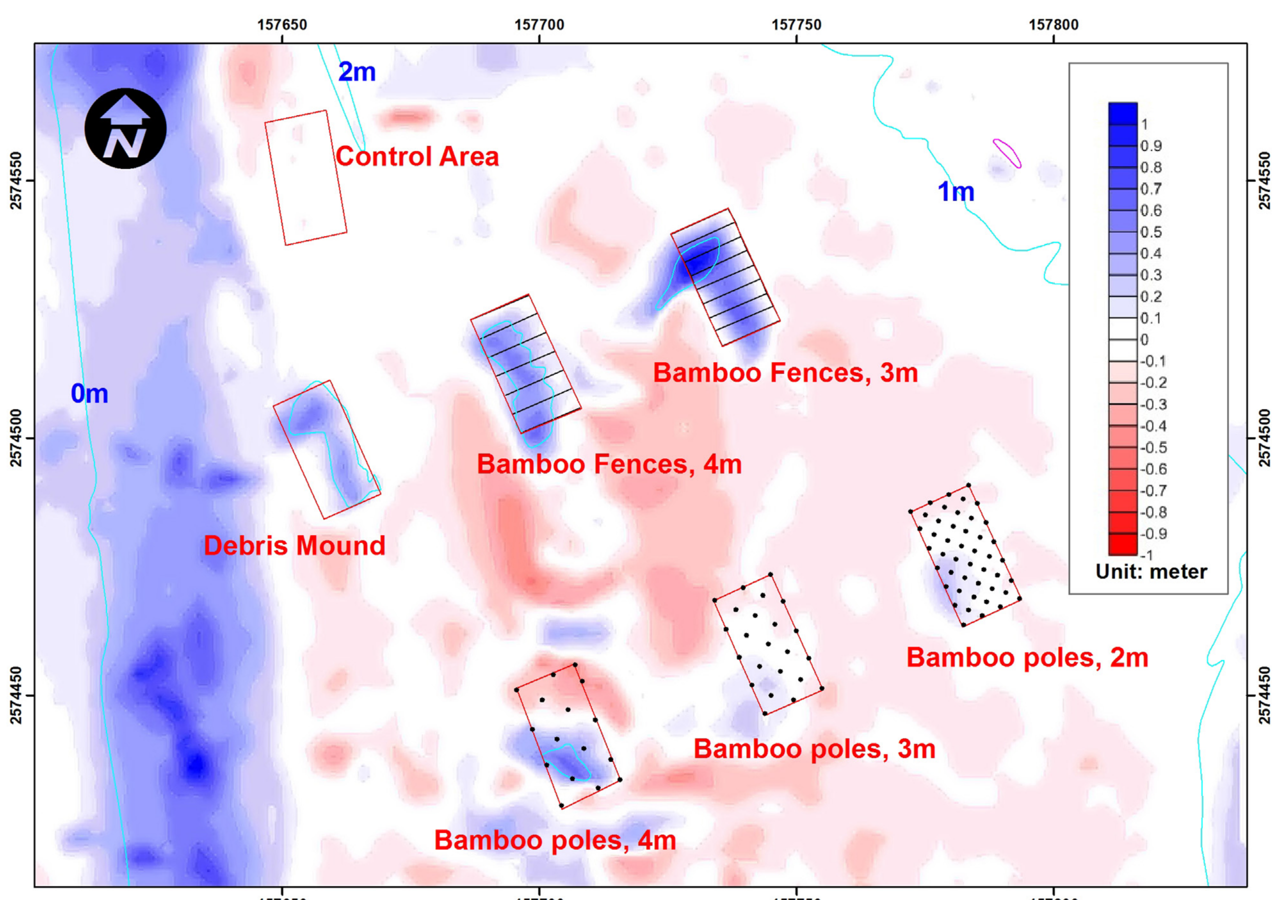

Fig. 3. Changes of the topography from November 13, 2011 to February 06, 2012 during the sand dune nourishment experiments.

entirely, with the result of a coast having a more or less natural appearance.

- Bamboo fences

Sand fences are one of the most common man made devices to affect the morphology and vegetation on sandy coasts. They are one of the few structures permitted in coastal conservation areas in many countries (Nordstrom, 2000). In the meantime, they are inexpensive and easy to emplace.

In the 2010–2011 period, two attempts of sand fencing in this region have failed. Among other possible reasons, we believed that one of them might be that the fences have too large porosity. As reported in Lin and Liou (2013), the one with a 75% porosity had trapped only marginal sands, while the other, of 66%, worked better. It is also possible that the period of their experiments were too short, as shown by Hotta et al. (1987), fences with any porosity will be buried after a sufficiently long time. To prevent the bush at the edge of a shelterbelt to be buried by sands, fences were used by the Forestry Bureau in Taiwan. The porosity of the fences used by them is often so small that all the sands were settled in front of the fences, and asymmetrical dunes were formed. As a result, the fences collapsed under the weight of the sand dunes. Once the fences collapse, the tourists might be injured by the remains. Drawing on wisdom from the past, we have decided that our fences should meet two prerequisites. In the first place, all the materials should be absorbed easily by the surroundings. Secondly, the fences should have adequate porosity so that the sands will be distributed more or less evenly within the fences.

In this field test, the whole fence was made of bamboo. All parts of the bamboo tree were used. Lattices of size 1×1 m with large openings were made using bamboo splints at first; the openings were then filled with bamboo stems with foliages. These lattices were then fixed to bamboo posts to work as bamboo fences. Once a dune has reached its designated height the posts are to be removed. The remaining bamboo stems and foliages are left to wither, and to be absorbed by the environment. The main idea is to use the bamboo foliages to fill up the lattice openings, so that the optimal fence porosity of 50% (Gravens et al., 2001) could be achieved. It is estimated that, about 1.5 kg/m of bamboo stems and foliages are to be used to have 50% porosity. The setup is shown in Fig. 3(b).

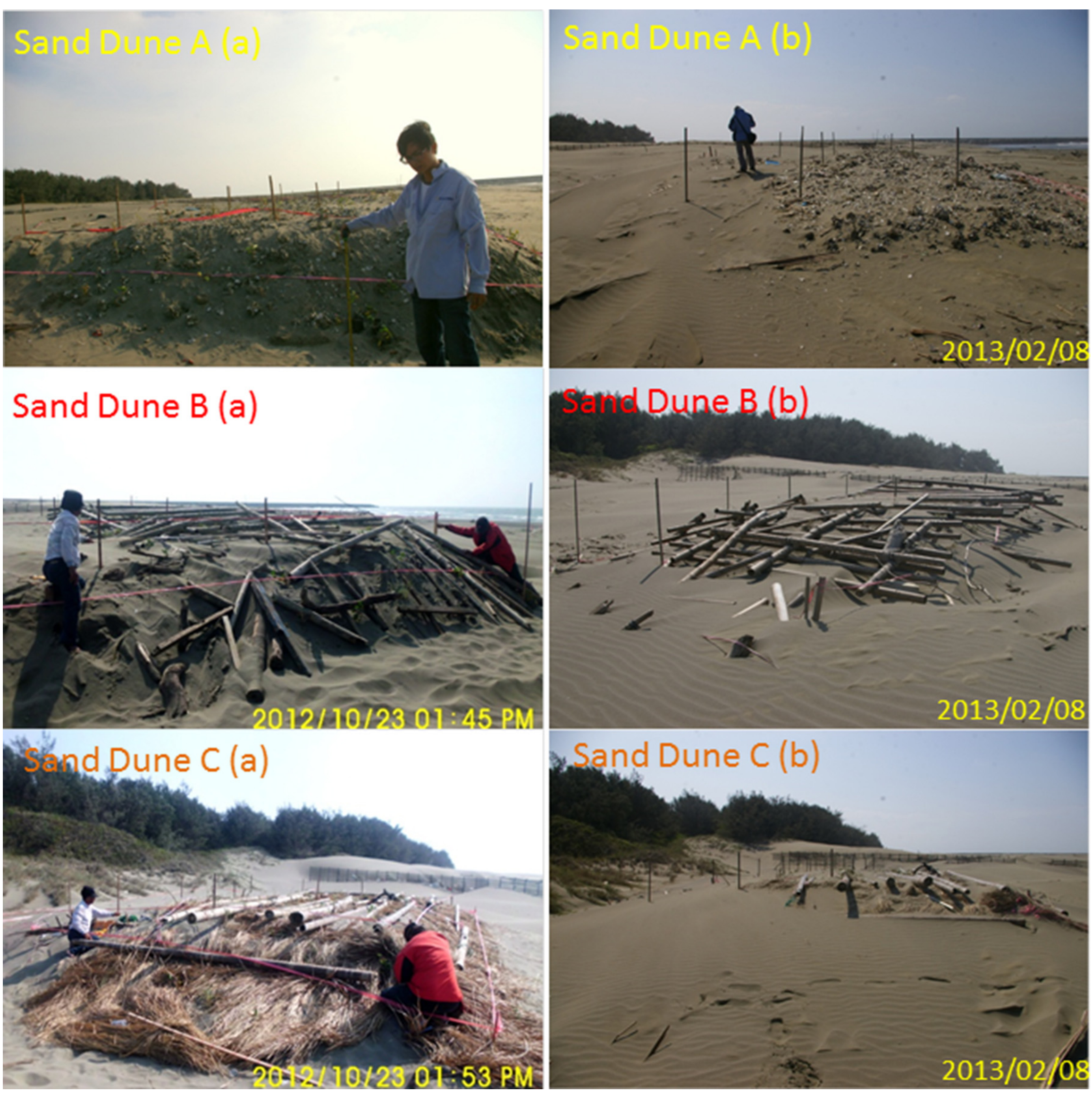

Fig. 4. Bulldozed sand dunes at the beginning (a) and end (b) of the stabilization experiment.

The distances between each row of the fences are also of importance. There is no definite specification in the literature about this distance. Usually, a distance that is 4 times the fence height is mentioned (Gravens et al., 2014). In this way, a faster sand trapping result at high wind speeds could be reached. Since there are many other factors affecting sand accumulation rate (Nordstrom, 2000), we have chosen two fields with spacing of 3 and 4 m for comparison.

2.2. Dune stabilization experiments

To minimize encroachment of the build-up sand dunes by wind, 3 different mulches were tested. The bulldozed dunes for the experiments all have the form of flattop pyramid, with a base of 10 × 10 m and a height of 1 m. The slopes of the 4 sides of each pyramid are approximately 1:2.5. The experimental site is at the southern side of the Bei-men beach. The 3 sand dunes in alignment are designated as sand dune A, B. and C in the following. The flat top of each sand dune is further divided into two parts. Whereas, the eastern parts without coverage are used as control, the western parts are protected by mulches. Materials used for the 3 mulches of sand dunes A, B, and C are, respectively, oyster shells, drift woods, and dried giant *Miscanthus*.

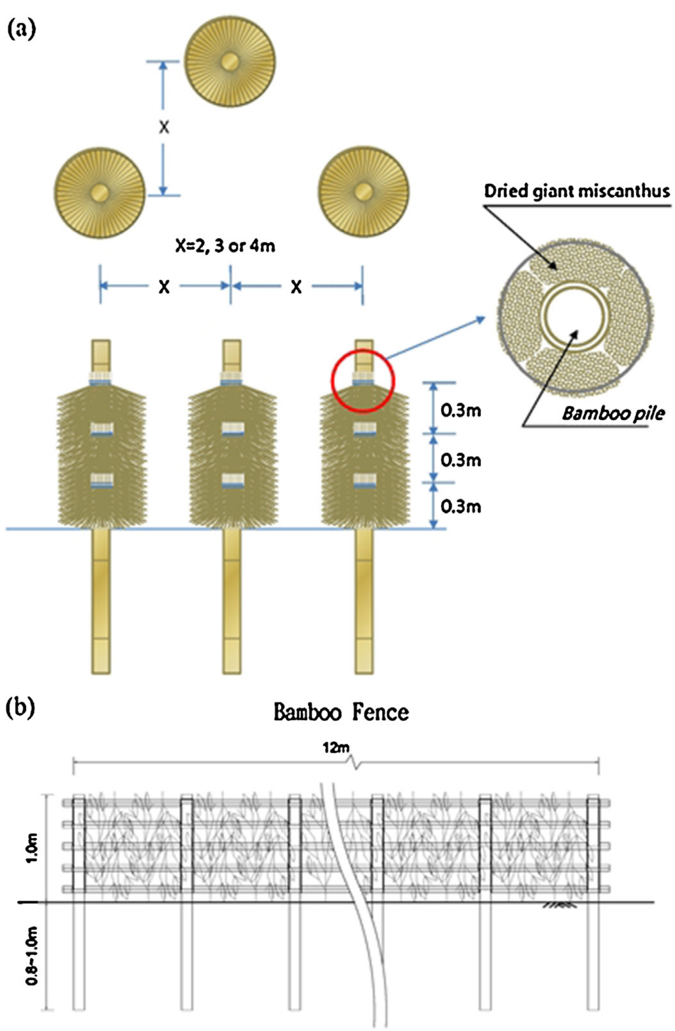

Fig. 5. Sketches of setups used in the sand dune nourishment experiments. (a) Bundles of dried giant *Miscanthus*, and (b) bamboo fence.

2.3. Biological sand fixation

Vegetation can enhance the stability of sand dunes, and, in the meantime, increase the surface roughness so that more aeolian sand will be trapped. Quite often, however, sand dunes have sparse vegetation due to the harsh environmental conditions they are subjected to. Transplantation can help to improve the situation, as many researchers have shown. Dahl et al. (1975), for example, have found that the man-built dunes with vegetative transplants have higher rates of success than those without. 2 indigenous plants, seashore vine morning glory (*Ipomoea pes-caprae*) and Littoral Spinegrass, were used in our experiment.

Generally speaking, the success of planting depends on the season. Spring and summer are the main growing seasons of the vegetation. However, since the experiments were started in fall, the chosen plants were first grown in a nursery garden and then transplanted onto the mulches. For comparison, the two plants were arranged in alternative rows of 1 m^2. There were 50 plants on each of the paved side of the 3 dunes.

3. Results and discussion

3.1. Sand dune nourishments

Changes of the nourished sand dunes were surveyed by a GPS model used in real time kinematic (RTK) modalities. 12 topographical surveys were carried out for this purpose. Fig. 4 shows the changes from November 13, 2011 to February 06, 2012. The results of each setup are summarized in the following:

(1) Dried giant *Miscanthus* bundles on bamboo posts-1

Sand trapping ability of this setup is rather poor, irrespective of the spacings of the bamboo posts. Although there are sands accumulated at the windward sides of the posts, the amount is too small to call them crescentic dunes. At the leeward side, strips of sands of about 1 m in length were also formed. None of the accumulated sands have heights exceeding 20 cm. Since sands in areas with no fencings were clearly seen to be lost through wind action, we consider this setup can work as a “wind erosion prevention” measure.

• Mounds of marine debris-1

As expected, pile-ups of the marine debris do help in retaining the sands. Soon after the pile-ups were completed, they began to trap sands at the windward side and the spacings were filled gradually. Finally, the whole pile-up was covered by sands, save some large-sized debris that protrudes from the dune. However, at the end of second month soon after the sands have reached the height of the debris, they stopped to accumulate. Afterwards, the amount of arrested sands decreased in a continuous way. Once the sands have filled the voids of the debris, no more sands can be captured. At the same time erosion sets in, leading, eventually, the tips of the larger debris to appear again.

• Bamboo fences-1

Sand fences have a long successful history. The main objective of our experiments is to determine the specific arrangements required for the climate on site. As mentioned before, 2 kinds of arrays of the fences were tested. The one is with arrays that are 3 m apart from each other, and the other is 4 m. It was found that for the 3 m case, after a period of a month and half, sands have accumulated up to a height of 1 m on the windward sides of the first three rows of the fences. For the rest rows the heights are

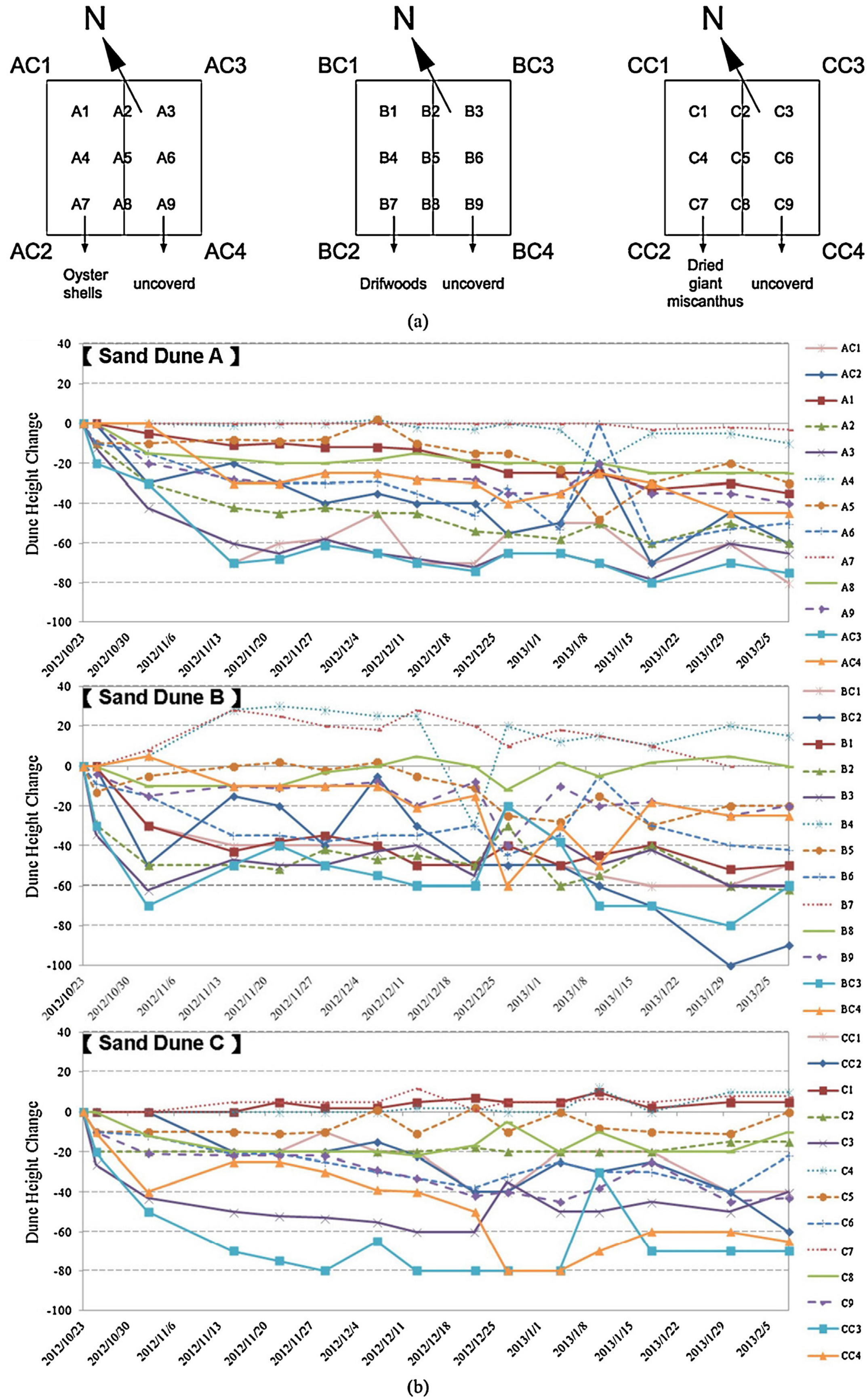

Fig. 6. The sand dune stabilization experiment. (a) The schemas of the setups and the locations of the monitoring points. (b) Changes of the sand dune heights during the experiment.

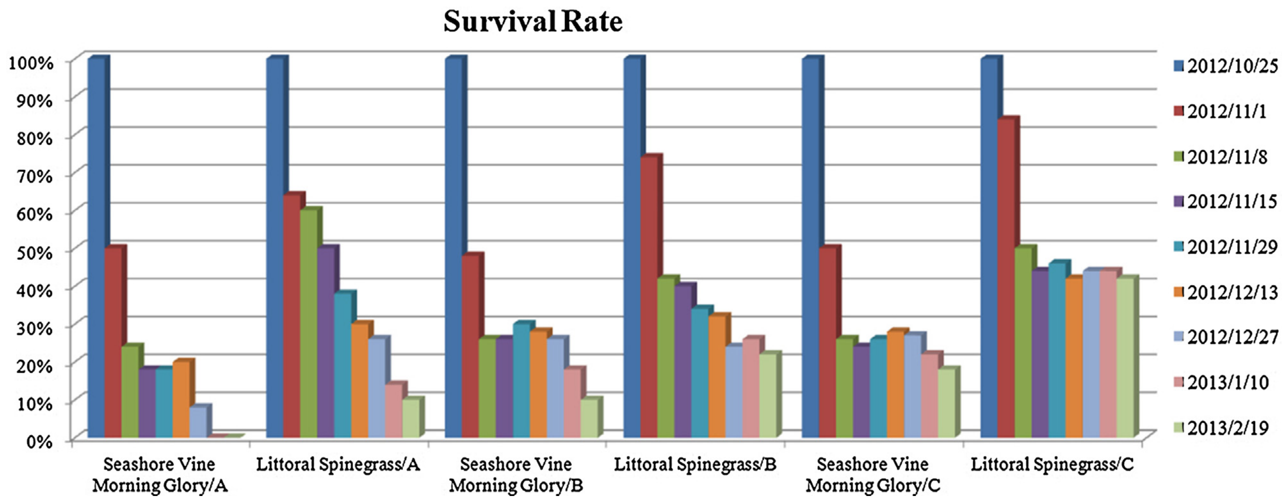

Fig. 7. The survival rate the transplant vegetation.

between 50–60 cm. 3 months after fencing, build-up sand dune began to migrate downwind, so that the tips of fences in the first two rows gradually appeared again. Meanwhile, the sand accumulations have the heights of 80–100 cm for the rest rows. On the other hand, nourished sand dunes by fences with 4 m intervals have a much flatter top. The height is also much lower, of round 40–50 cm. It is estimated that the fences with 3 m intervals can arrest about 1.89 times more sands than those with 4 m intervals within the experimental period. As mentioned earlier, in majority of the literature the distance between the fence rows is 4 times the fence height. However, our experiments here show that a 3 m distance yields much better results. This demonstrates once again that the efficiency of sand fencing is locality dependent.

3.2. Sand dune stabilization

Experiments on stabilization of man-made sand dune were carried out from October 23, 2012 to February 8, 2013. Fig. 5(a) shows the 3 setups at the beginning, and Fig. 5(b) their status at the end of the experiments. Changes of the sand dunes were measured with rulers once a week. Each sand dune has 13 monitoring points, including 4 of the corners and 9 on the surface of the mounds. This is shown schematically in Fig. 6(a).

Changes of sand dune heights at each monitoring point with time are shown in Fig. 6(b). The most severe erosions are at the eastern upper corners (AC3, BC3, and CC3), where wind actions are the strongest. It can be seen in Fig. 6(b) that, sand dunes have decreased 80 cm in heights. It should be noted that, although the general trend is erosion, the sand carried by wind from adjacent dunes may land here, so that the net loss due to wind erosion is unknown. We believe that, this is the reason why the curves in Fig. 6(b) are fluctuating, showing alternating accretion and erosion has occurred. At the end of our experiment, sand of the 3 control areas have avalanches down the slop, and all the uncovered parts of the dunes were destroyed.

Pavement of oyster shells on sand dune A was intended to reduce erosion. However, on the western upper corner, which was on the windward side, the height of the dune has reduced 30 cm. This is because that, the voids left by the oyster shells are too large so that there is still ample room for winds to blow the sand away. The middle and lower parts of the dune have also lost some small amounts of sand. A reduction of original thickness of 10 cm was found.

Sand dune B has a mulch made of driftwoods, and the spacing between these driftwoods are too large so that the dune changes its form continuously. It was found that, within a month the

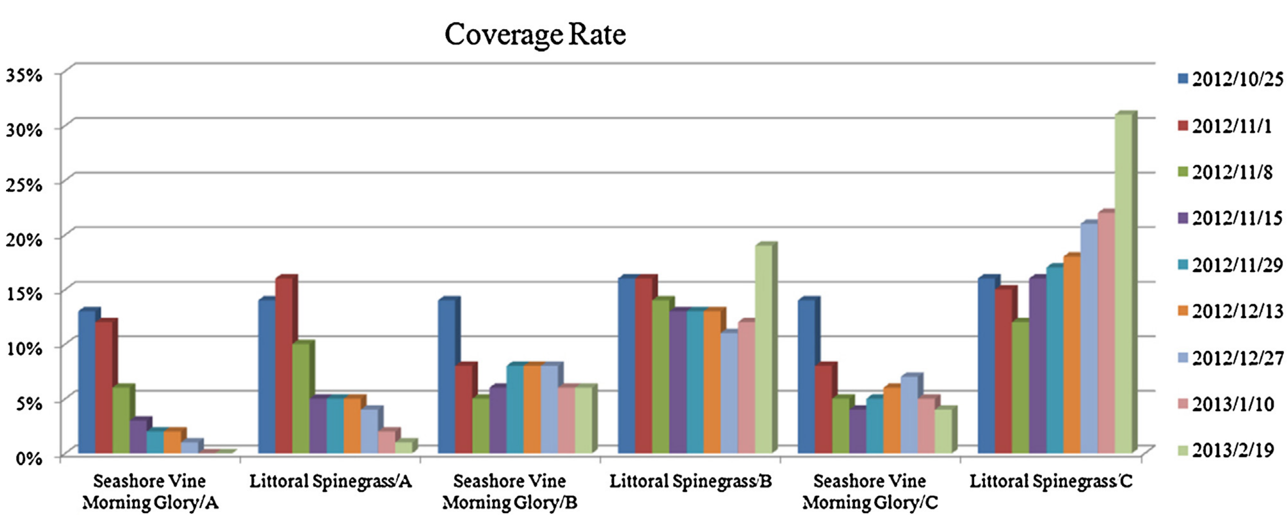

Fig. 8. The coverage rate of the transplant vegetation.

Table 3
Results of the sand dune restoration experiments (** the best setup).

Experiments	Result		
Sand dune nourishments	Poor	Average	Excellent
1. Bundles of dried giant *Miscanthus* on bamboo pole			
A. Spacing 2 m	y		
B. Spacing 3 m	y		
C. Spacing 4 m	y		
2. Mounds of marine debris		y	
3. Bamboo fences			
A. Spacing 3 m			y/**
B. Spacing 4 m			y
Dune stabilization and biological sand fixation			
1. Oyster shell pavement	y		
A. Littoral Spinegrass (survival rate/coverage rate)	10%/1%		
B. Seashore vine morning glory (survival rate/ coverage rate)	0%/0%		
2. Mulch of drift woods		y	
A. Littoral Spinegrass (survival rate/coverage rate)	22%/ 19%		
B. Seashore vine morning glory (survival rate/ coverage rate)	10%/6%		
3. Dried giant *Miscanthus* pavement			y/**
A. Littoral Spinegrass (survival rate/coverage rate)	42%/ 31%**		
B. Seashore vine morning glory (survival rate/ coverage rate)	18%/4%		

windward sides (BC1 and B1) have decreased 40 cm on thickness, while the middle part of the dune has gained 30 cm. This means that, part of the eroded sands were transported and settled downwind, making the dune to migrate slowly southwards.

Dried giant *Miscanthus* not only keeps sand dune C intact, but has also trapped and added more sands to it. This is true even after the strongest winter monsoon winds experienced during the experiment. Comparing the results, it is concluded that the setup C performs the best in stabilizing and nourishing sand dune, followed by setup B, and setup A is the least effective one.

3.3. Vegetation experiment

In this paper, we use the term 'survival rate' to evaluate the success/failure of the vegetation. Here, the survival rate is defined as the number of living plants to the total number of transplanted plants. Although watering and/or fertilizing can increase its chance of survival, no such action was taken for the vegetation. First of all, fresh water is nonexistent here and must be shipped from land, it is therefore considered as too cost-intensive. Secondly, fertilizer may easily leach through porous sand, pollute groundwater, and affect the quality of our water.

Although the 3 man-made sand dunes were subjected to the same climate condition, it can be seen in Fig. 7 that the same species planted on them have different survival rates. For each dune, the Littoral Spinegrass always has a higher survival rate than the seashore vine morning glory. The Littoral Spinegrass planted on dried giant *Miscanthus* (sand dune C) has the highest survival rate of 42%, whereas that of the seashore vine glory is only 18%. In whole, plants on sand dune C have the highest survival rate, followed by sand dune B, and sand dune A has the lowest.

It was also found that vegetation on the windward sides did not survive the test. All of them withered eventually. Those on the lee sides have a better chance to survive. We conclude that, using dried giant *Miscanthus* as mulch has the advantage of becoming

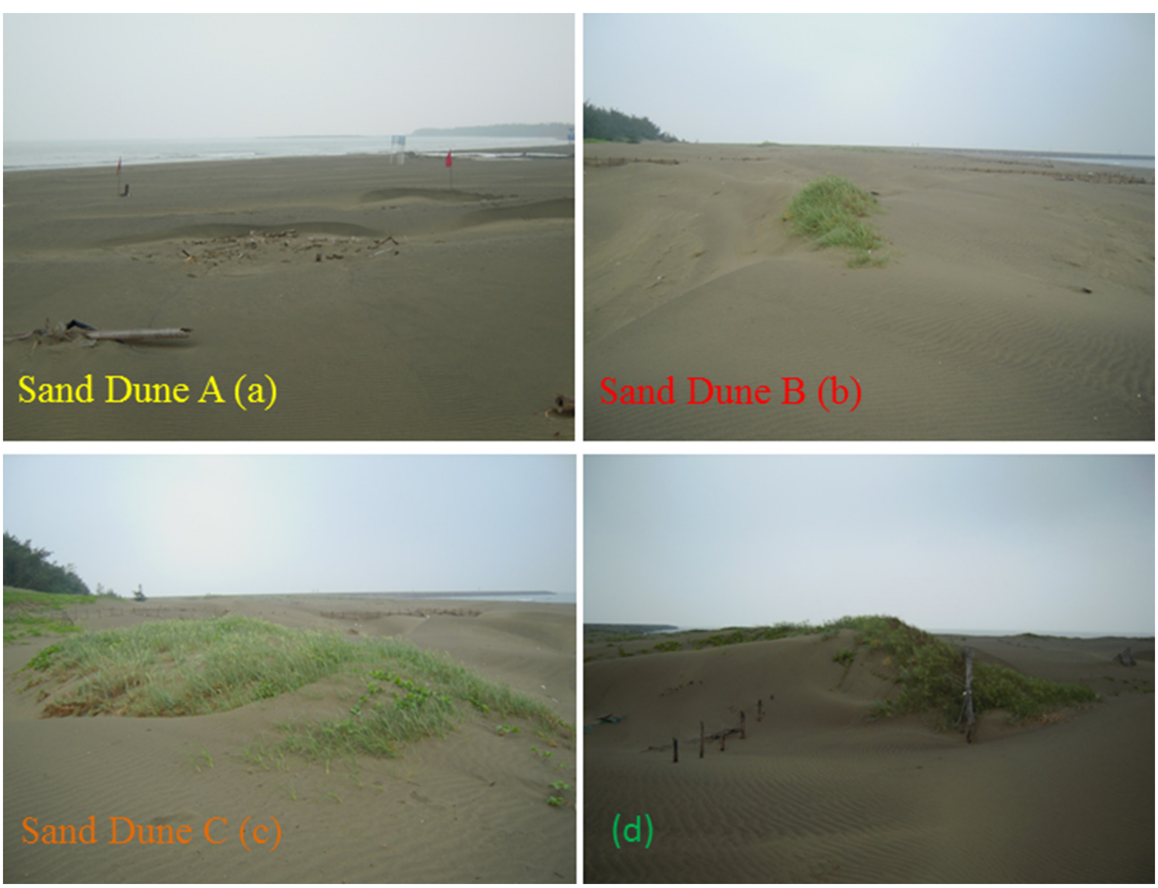

Fig. 9. The present status of (a) sand dune A (oyster shells), (b) sand dune B (drift woods), and (c) sand dune C (dried giant *Miscanthus*), and (d) a recently nourished sand dune.

saturated in the humid sea air overnight, providing ample water needed by the plants during the day.

3.4. Measuring vegetation coverage rate

The 3 basic ways to measure vegetation cover are points, lines, and plots. In this experiment, we used the line method to measure vegetation covers of the dunes. Coverage rate is defined here as the length covered with plants to the distance from the first to the last plant on the surface of dunes. Changes of coverage rates of the planned plants with time on each sand dune are shown in Fig. 8.

With interchanging accretion and erosion, sand dune A was itself unstable and most of the plants on it withered at the end. The coverage rates of sand dune B and C decreased in the first 3 weeks. Afterward, the trend reversed and transplant vegetation started to grow. On all the dunes, Littoral Spinegrass always have faster growing rates than those of seashore vine morning glory. Sand dune C has the highest vegetation cover, followed by sand dune B, and then A, in accordance with the stabilities of the dunes. Table 3 summarizes the results of the experiments.

3.5. The follow-ups

2 years after the project was completed, we revisited the site. Fig. 9 shows the present status of the 3 stabilized dunes. Sand dune A with all its transplant vegetations disappeared. On the paved side of sand dune B, only one-third of the planted Littoral Spinegrass has survived, and no seashore vine morning glory can be found. Sand dune C has merged into the surrounding nature scene, but its original form can still be vaguely recognized. The majority of the plants on sand dune C is Littoral Spinegrass, with little seashore vine morning glory scattered around. Convinced by the success of the experiments, the Forestry Bureau has used our method in this region since 2013. Fig. 9(d) shows one of the restored sand dunes and the restoration is still ongoing.

4. Conclusions

In the past few decades, the Bei-men barrier island is found to retreat rapidly. The authorities decided to find the most ecologically sound, cost efficient way to prevent its further lost. Since only soft-engineering measures are allowed, we focus our attention on the restoration of sand dunes. To determine which locally available materials can be used, a series of experiments were carried out.

Based upon these results, it is therefore concluded that, to restore and nourish sand dunes on the barrier island of Bei-men coast, the best way would be:

1. Accumulate aeolian sands using fences made of bamboos, with a spacing of 3 m and 1 m in height. It would help in retaining the sand deposits and formed sand dunes. However, our results showed that the efficiency of the sand dune nourishments is determined by the local factors. It is therefore suggested that field experiments should be conducted first before the emplacement of fences along large areas.
2. Once the sand dune reaches the target height, pull out the bamboo stems and leave the rest materials to degenerate and absorb by the environment.
3. Use dried giant *Miscanthus* as mulch for the new-grown sand dunes, and plant Littoral Spinegrass on the dunes. The paved and transplanted plants can help to stabilize the dunes, making them more resistant to marine and wind forces. In the meantime, it helps to prevent the barrier island from moving landwards.
4. It is also worth mentioning that the use of dried giant *Miscanthus* as a mulch on sand dune has the advantages of (1) preventing the sand dune from wind erosion, (2) keeping it stable, and (3) providing better surroundings for vegetation growth. We believe that this measure can be a valuable solution for some coast regions where irrigation facility for the transplant vegetation does not exist.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecoleng.2014.09.038.

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